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CFD analyses for passive house with Trombe wall and impact to energy demand

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ABSTRACT

The paper deals with a comprehensive, three-dimensional numerical CFD analysis of temperature fields in Trombe wall and in the adjacent room for several days of a typical meteorological year (TMY) *for a moderate continental climate*. Construction of the Trombe wall is optimized, using different types of glassing on the outside of the wall. For summer day, the glass is considered to be covered with PV stripes during the daylight in order to prevent overheating. The central concrete core of the wall is covered with a layer of dark paint, on the outside, to improve absorptivity of the wall. The Trombe wall is oriented on south side of the house, and designed with openings with flaps in concrete core. Those openings are simulated in opened and closed positions. The *U*-values of the house envelope are considered according to passive house standards. Temperature fields in concrete core and in the room with Trombe wall are simulated, as well as velocity fields. According to these results, analysis of energy savings potential is performed.

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1. Introduction

The main impeller for this research was the study that had been performed few years ago [1], which has shown the great contribution of Trombe wall in total energy needs for heating for Belgrade weather data. That study had also shown that the Trombe wall is a great source of heating loads in summer which is not desirable, so this paper considers combination of glassing and covers that are optimal for both winter and summer conditions. Using CFD in this kind of problems, it is possible to make an initial prediction of temperature and velocity fields in the room and also choose the configuration that best fits the outer weather conditions.

Five typical cases are considered: two winter days with clear single glassing on the Trombe wall and flaps closed in wall, winter and spring day with flaps opened in concrete core and closed in glassing, and summer day with glassing which is totally protected with PV stripes, but with flaps opened in glassing, and closed in concrete core of the Trombe wall.

2. Model of passive house with Trombe wall

The model of passive house with Trombe wall that was simulated is a simple room with Trombe wall on its south side: width 5000 mm × depth 6000 mm (plus 350 mm for the Trombe wall) × height 3000 mm. It is simulated for Belgrade, Serbia, weather conditions.

The Trombe wall consists of: 4 mm simple glass, 150 mm air layer, 2 mm black painted cover and 200 mm concrete wall. The absorptivity (and emissivity) of the concrete wall and black paint external surfaces is assumed to be 1.0 in accordance with the characteristics of the material (Table 1).

There are six equal air vents with flaps in the wall, located in the four corners of the wall and its middle top and bottom, Fig. 1. Their size is 300 mm × 200 mm and their distances from the corresponding wall edges are 300 mm. There are also six openings of the same size in the outer glass, with flaps, for ventilation and overheating prevention. These flaps can be either opened or closed depending on the operating conditions. The remaining walls (north, east and west) are composite, well-insulated and 400 mm thick, according to passive house standards [2]. The house also has a window, 2200 mm × 1200 mm, and a door, 900 mm × 2100 mm. The roof and floor are also composite, insulated and 400 mm thick. The envelope is considered as constructed according to typical passive house standards for walls, floor and roof with *U*-values 0.14 W/m^2 K, for windows *U*-values 0.75 W/m^2 K and for front door with *U*-value 0.75 W/m^2 K.

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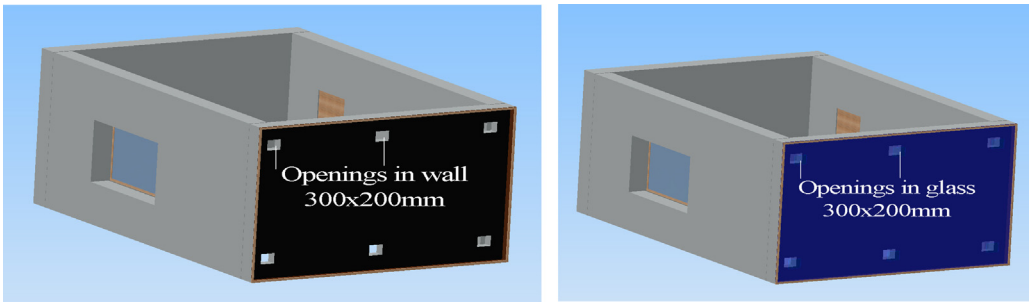

Fig. 1. 3D model of the house with openings in concrete core (left) and in glass (right).

Table 1
Material properties.

Material	Density [kg/m^3]	Specific heat [J/kg K]	Thermal conductivity [W/mK]	Absorption coefficient [m^{-1}]	Refractive index [–]
Air	Ideal gas	1006.43	0.0242	0	1
Concrete	2000	960	1.5	1.7	0
Black paint	2100	1050	1.6	1.7	0
Glass	2500	840	0.81	200	1.5
Wood	700	2310	0.173	0.4	0

3. Basic assumptions, initial and boundary conditions

In order to determine temperature distributions in the room and how to use the flaps of air vents adequately, several different situations with different boundary conditions and settings were investigated. In particular, two cases on a regular winter days (January 1st and January 15th) were simulated with closed flaps of air vents in concrete core, in steady-state and transient, case 1 and case 2, respectively. In order to obtain a complete picture of the advantages and disadvantages of this system on a yearly level three regular days in three different seasons were selected, namely, in winter January 15th, in spring April 15th, and in summer July 9th. Two different configurations on a regular winter days were simulated, with closed (cases 1 and 2) and one with open flaps of air vents (case 3). Transitional period between winter and summer is considered through the Case 4 (April 15th), when flaps in concrete core are opened. Case 5 corresponds to a regular summer day with open openings in the outer glass and PV stripes along the glass that are meant to prevent overheating of the room.

The following assumptions were adopted for every considered model. The governing Navier–Stokes equations combined with RANS turbulence model and radiation model were solved in the commercial three-dimensional, parallel, finite-volume solver ANSYS FLUENT v14.0. The fluid, air, was regarded as incompressible ideal gas. The solver was pressure based with coupled pressure–velocity coupling scheme. All spatial discretizations were of second order. The cases 1, 3 and 5 were solved as stationary, at the same time of the day, namely 1 p.m. In order to simulate the accumulation of heat as accurately as possible, some cases were solved as transient, during the same time of day, starting from 9 a.m. until 8 p.m. (cases 2 and 4). This approach significantly prolongs the computations and increases necessary computational resources but, on the other hand, offers insight into data that could not be obtained in steady-state simulations and are crucial for accurate assessment of the system.

A widely used, two-equation, standard k–ε model was used for closing the set of governing equations. The influence of radiation was implemented through DO radiation model and the use of solar calculator for Belgrade at a considered time of the year and day. DO radiation model allows the solutions of radiation at semi-transparent walls, as well with surface-to-surface radiation problems [3]. In Ansys radiation model dialog it is possible to check the Solar calculator options, which is used to predict the Sun position vector and illumination parameters. For more detailed information, please look at ANSYS FLUENT Theory Guide [3]. In this research, the Boussinesq assumption was used in order to consider the buoyancy caused by temperature differences. No other heat sources were considered.

Several user-defined functions were developed in order to simulate the transient boundary conditions, i.e. the change in the temperatures of outer air and ground during the day (Table 2).

The mathematical relations were obtained by interpolating the random model values typical for the considered days in Belgrade, Figs. 4 and 8. The functions were written in C programming language, compiled from ANSYS FLUENT and assigned to appropriate boundaries.

The initial conditions for the simulations were the converged solutions from the steady state analysis at 9 a.m.

The boundary conditions are given in Table 3.

4. Mathematical background

The problems of indoor airflow and convective and radiative heat transfer are governed by the conservation equations for mass, momentum in each flow direction and energy. In addition, the airflow is considered predominantly turbulent [4].

Mass conservation equation for 3D airflow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho u)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{1}$$

where ρ[kg/m^3] is air density, and u, υ, w are velocity components in x, y and z direction respectively. For the incompressible airflow, the air density is constant (the local variations in density are negligible to the local velocity variation), so Eq. (1) can be written as:

$$\frac{\partial u}{\partial x} + \frac{\partial \upsilon}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

Navier–Stokes equation for incompressible 3D airflow with constant viscosity (momentum conservation equations):

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \upsilon\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + X \tag{3.1}$$

$$\rho\left(\frac{\partial \upsilon}{\partial t} + u\frac{\partial \upsilon}{\partial x} + \upsilon\frac{\partial \upsilon}{\partial y} + w\frac{\partial \upsilon}{\partial z}\right) = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 \upsilon}{\partial x^2} + \frac{\partial^2 \upsilon}{\partial y^2} + \frac{\partial^2 \upsilon}{\partial z^2}\right) + Y \tag{3.2}$$

Table 2
Measured values for outer air and ground temperature – average weather data.

	9 h		13 h		16 h		20 h	
	T_{air} [°C]	T_{ground} [°C]	T_{air} [°C]	T_{ground} [°C]	T_{air} [°C]	T_{ground} [°C]	T_{air} [°C]	T_{ground} [°C]
January	−9	−11	−3.4	−5.7	−4.4	−6.1	−7.1	−7.7
April	3.1	−1.2	1.8	0.4	3.8	1.8	3.3	1.6

Table 3
Summary of boundary conditions used in CFD simulations.

Partition	Wall thickness [mm]	Heat transfer coefficient [W/m² K]	Temperature [°C]	External emissivity	Internal emissivity	Radiation BC type
Floor	400	0.14	T_{floor}	0.9	0.3	Opaque
Walls and ceiling	400	0.14	T_{air}	0.9	0.3	Opaque
Window	4	0.75	T_{air}	1	1	Semi-transparent
Door	50	–	T_{air}	–	0.3	Opaque
Trombe wall glass pane	4	5.2	T_{air}	1	1	Semi-transparent
Trombe wall black paint	2	–	–	–	1	Opaque

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+\upsilon\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right) = -\frac{\partial P}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+Z \quad (3.3)$$

where X ($X=0$), Y ($Y=-\rho g$), and Z ($Z=0$) are projections of body force F in x, y and z direction, and P is pressure.

Energy conservation equation is applied for the air, and given in averaged, filtered form as follows [3]:

$$\frac{\partial\rho\bar{h}_s}{\partial t}+\frac{\partial\rho\overline{u_i h_s}}{\partial x_i}-\frac{\partial\bar{P}}{\partial t}-u_j\frac{\partial\bar{P}}{\partial t}-\bar{u}_j\frac{\partial\bar{P}}{\partial x_i}-\frac{\partial}{\partial x_i}\left(\lambda\frac{\partial\bar{T}}{\partial x_i}\right) = -\frac{\partial}{\partial x_j}(\rho(\overline{u_i h_s}-\bar{u}_i\bar{h}_s)) \quad (4)$$

where are velocity components in T is temperature, h_s is sensible enthalpy and λ is thermal conductivity.

Due to the turbulent nature of the airflow, it is necessary to introduce Reynolds decomposition into the continuity equation:

$$u_i=\bar{u}_i+u_i' \quad (5)$$

where $\bar{u}_i$ is ensemble average of velocity for steady flow, and u_i' is fluctuation velocity.

The governing equations for turbulent flow are:

$$\frac{\partial\bar{u}_i}{\partial x_i}=0 \quad (6)$$

$$\rho\frac{\partial\bar{u}_i}{\partial t}+\rho\bar{u}_j\frac{\partial\bar{u}_j}{\partial x_j}=-\frac{\partial\bar{P}}{\partial x_j}+\frac{\partial\tau_{ij}}{\partial x_j}+\rho\bar{F}_i \quad (7)$$

where τ_{ij} is viscous stress tensor:

$$\tau_{ij}=2\mu s_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \quad (8)$$

If (5)–(8) are combined, Reynolds-averaged Navier Stokes equation (RANS) is:

$$\rho\frac{\partial\bar{u}_i}{\partial t}+\rho\bar{u}_j\frac{\partial\bar{u}_j}{\partial x_j}=-\frac{\partial\bar{P}}{\partial x_j}+\frac{\partial(2\mu s_{ij}-\rho\overline{u_i'u_j'})}{\partial x_j}+\rho\bar{F}_i \quad (9)$$

where $\rho\overline{u_i'u_j'}$ is Reynolds stress tensor.

Standard k–ε model was used for closing the set of governing equations. The k–ε model is a turbulence model in which transport equations are solved for the turbulent kinetic energy k and its dissipation rate ε. [5] It combines ρ, k and ε with turbulent viscosity μ_t using constant c_μ :

$$\mu_t=c_\mu\rho\frac{k^2}{\varepsilon} \quad (10)$$

5. Simulation results and analysis

Case 1:

The steady-state simulation is performed for typical winter day (January 1st at 1 p.m.). Flaps in concrete core and in glassing are closed. For sun simulation, sun calculator existing in Fluent is used. Fig. 2 shows temperature field in the Trombe wall and in the room.

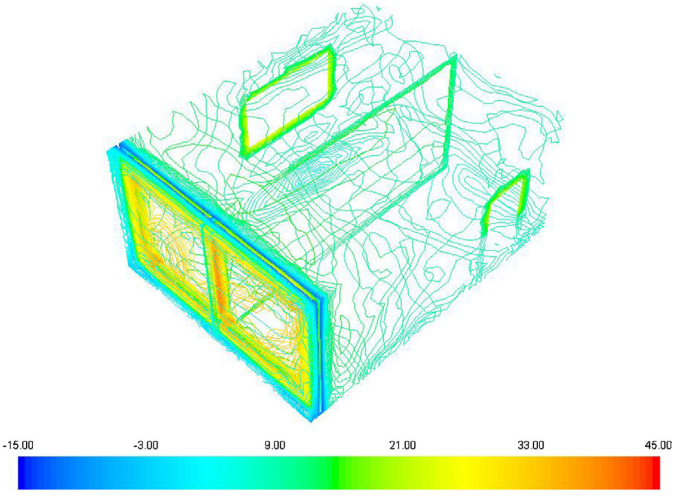

Fig. 2. Temperature distribution in the room and in Trombe wall for case 1 [°C].

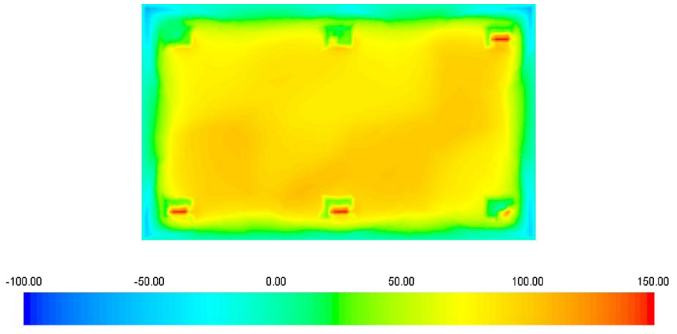

Fig. 3. Radiation heat flux on internal surface of concrete core for case 1 [W/m²].

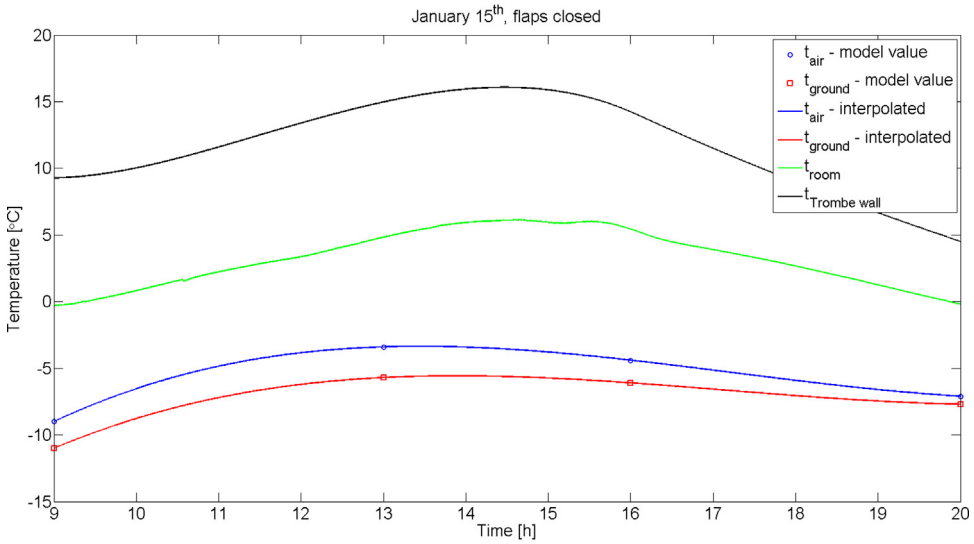

Fig. 4. Temperature distribution in the room and in Trombe wall for case 2 with transient conditions.

The average temperature in the room is simulated for the central point of the room (C-point in continuation), and for case 1, for partially cloudy weather (Sun Direction Vector: −0.308094, *Y*: 0.341061, *Z*: 0.888119 and sunshine factor 0.75) is 13.6 °C.

Fig. 3 shows radiation heat flux on internal surface of Trombe wall for case 1 (flaps closed). The average radiation heat flux on this surface is around 69.5 W/m^2.

Case 2:

In order to simulate the accumulation of heat as accurately as possible, the simulation is also preformed as transient, for January 15th during the day, starting from 9 a.m. until 8 p.m. and results are presented in Fig. 4. Flaps in concrete core and in glassing are closed. The average temperature in Trombe wall varies from 4.52 °C at 8 p.m. to 14.7 °C at 1 p.m.

Case 3:

The steady-state simulation is performed for typical winter day (January 1st at 1 p.m.). Flaps in concrete core are opened and flaps in glassing are closed. Again, for sun simulation, the sun calculator is used. Fig. 5 shows temperature field in the Trombe wall and in the room. The average temperature in the room in C-point, for case 3, for partially cloudy weather (same insolation conditions as in the previous case) is 14.7 °C.

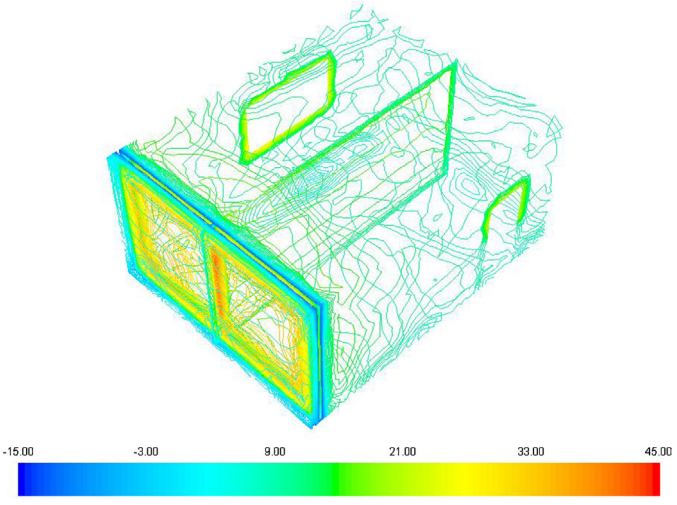

Fig. 5. Temperature field for case 3 with opened flaps in concrete core [°C].

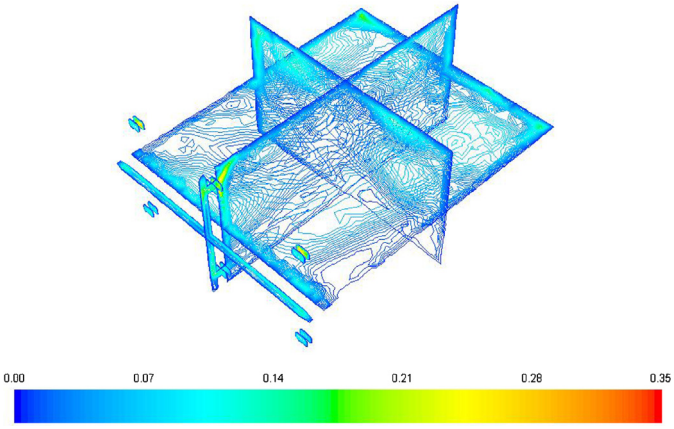

Fig. 6. Velocity contours distribution in Trombe wall and in room [m/s].

Airflow in the room and in the Trombe wall is natural, driven only by density stratification, caused by temperature differences along the room height. Fig. 6 shows velocity field for Case 3 with opened flaps in concrete core and it can be seen that velocity varies from ca. 0.1 m/s to 0.2 m/s in Trombe wall.

The result of simulation for radiation heat flux [W/m^2] on the internal surface of concrete core for case with opened flaps in the core is presented in Fig. 7. The average value of radiation heat flux is around 68.1 W/m^2.

Case 4:

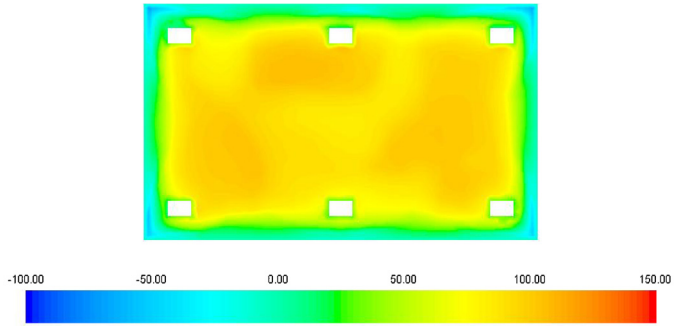

Fig. 7. Radiation heat flux on internal surface of concrete core for case 3 [W/m^2].

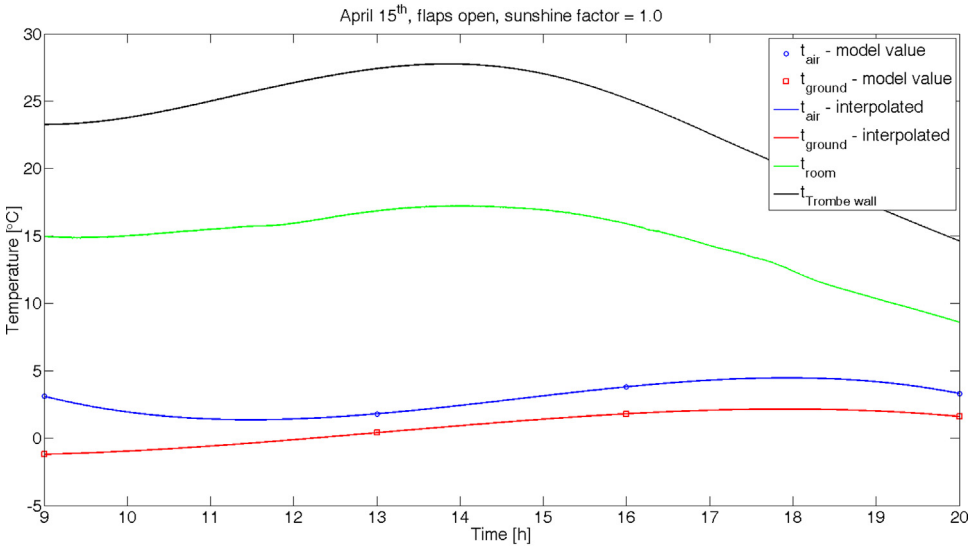

Fig. 8. Temperature distribution in the room and in Trombe wall for case 4 for transient conditions.

The simulation of transient process is also preformed for transitional period between winter and summer, for April 15th during the day, starting from 9 a.m. until 8 p.m. and results are presented in Fig. 8. Flaps in concrete core are opened and flaps in glassing are closed. The average temperature in Trombe wall varies from 14.62 °C at 8 p.m. to 27.41 °C at 1 p.m., and maximum average temperature that can be reached in room is around 21.69 °C.

According to these results, the flaps in concrete core should be closed from 4 p.m. to 9 a.m. in order to prevent the cooling of the room, for the Case 4.

Case 5:

This case represents a typical summer day (July 15th at 1 p.m.) where the flaps in concrete core are closed to avoid overheating of the room, and flaps in outside glassing of the Trombe wall are opened, and glassing is totally covered with PV stripes as a protector from direct sun. Simulation was steady-state and has shown that PV stripes have a big influence on overheating protection, which is shown in Figs. 9 and 10. The average temperature in C-point is 29.8 °C.

During the summer day, the average temperature in concrete core of Trombe wall is around 32–35 °C, due to PV covers on the outside of the glassing. The temperature field on the outside of concrete core is shown in Fig. 10.

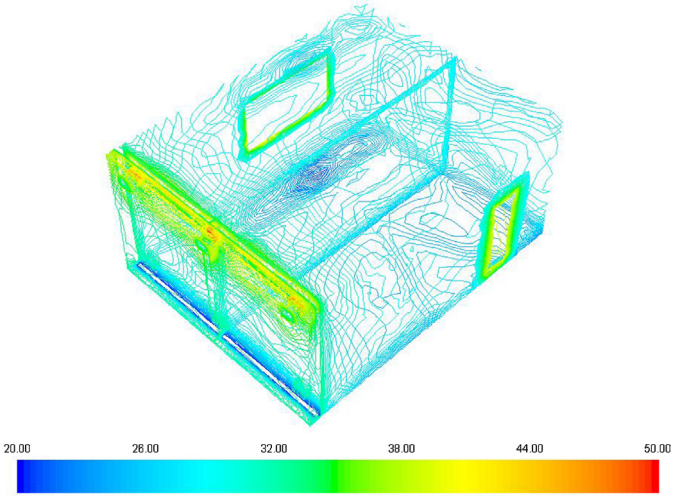

Fig. 9. Temperature field for case 5 with PV stripes [°C].

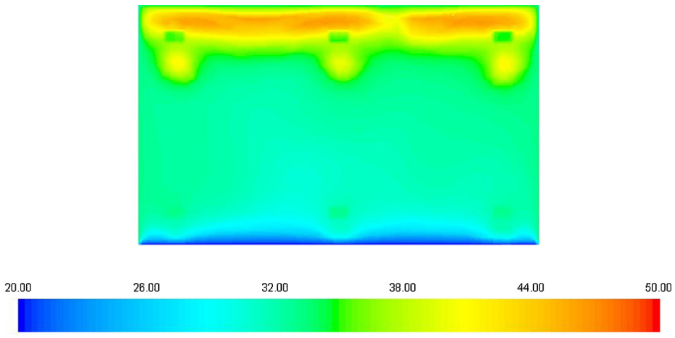

Fig. 10. Temperature field on the outer side of concrete core [°C].

Velocity field in Trombe wall is simulated with assumption that the inlet wind speed is 0.5 m/s. The velocity vectors distribution in the room and Trombe wall is shown in Fig. 11.

Finally, the radiation heat flux [W/m^2] on the internal surface of concrete core for summer case with PV strips is presented in Fig. 12. The average value of radiation heat flux is around 24.2 W/m^2, which appears as a result of the significant influence of PV stripes as an external protection from direct sun.

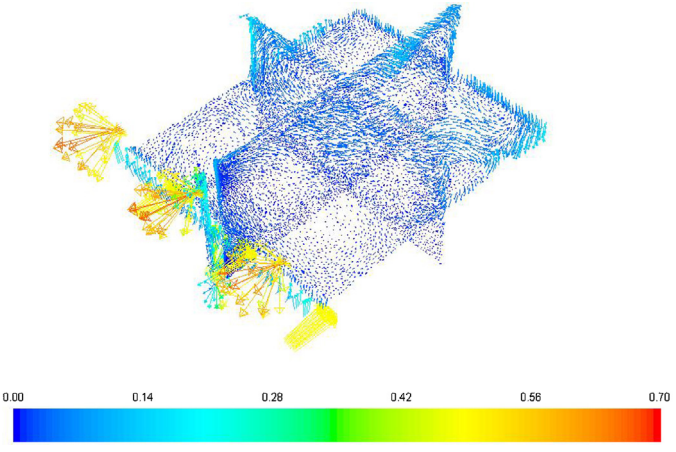

Fig. 11. The velocity vectors distribution in the room and Trombe wall for case 5 [m/s].

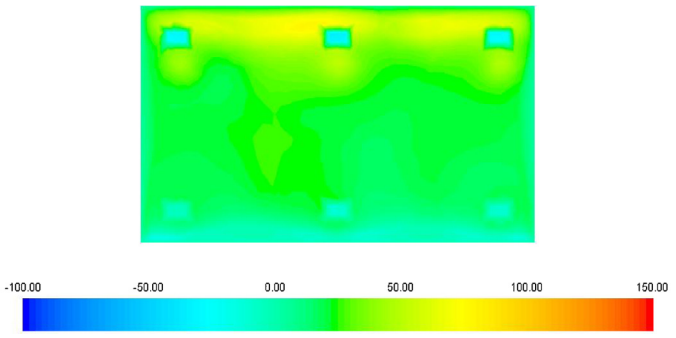

Fig. 12. The radiation heat flux on internal surface of concrete core for case 5 [W/m^2].

6. Conclusions

Simulations have shown a big impact of Trombe wall on the temperature field inside a model house for Belgrade weather data. The contribution of Trombe wall in winter conditions is huge (it is shown that temperature in the room is around 14.7 °C for Case 2).

However, in summer conditions, Trombe wall is an additional source of heat loads. It is possible to achieve acceptable temperature in the room (around 29.8 °C) with PV stripes as covered system on the outside of the Trombe wall, but it is still necessary to cool down the house till the temperature reaches 26 °C. Nevertheless, it is important to emphasize that the contribution of PV strips in electricity production needed for cooling devices operation is significant (c.a. 60% per summer day, if efficiency of PV stripes is 7%, covered vertical area of Trombe glassing is 14.64 m^2, average insolation on vertical surface, south oriented c.a. 3.3 kWh/m^2 per average summer day, average energy for cooling devices c.a. 1 kW/h and average working hours 36 h/week).

Therefore, Trombe wall is a good solution for Belgrade weather data, but for drawing the final conclusion, it is necessary to perform a detailed optimization of energy consumption for the typical meteorological year and then decide what is higher, additional energy necessary for cooling or the benefit of heating energy consumption reduction and contribution of RES in total primary energy.

Acknowledgments

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